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Exposing America: Comparative assessments of ionizing radiation doses to U.S. populations from nuclear and non-nuclear industries

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Abstract

The American public knows little about radiation exposures from either the commercial nuclear fuel cycle or non-nuclear (conventional) industries. Yet, many oppose commercial nuclear energy because of fear of ionizing radiation. Exposing America to education about normal radiation received from non-nuclear industries may help mitigate public concern over commercial nuclear generation, improving acceptance of this source of electricity for an energy-challenged 21st century. Using data and models developed from a variety of reliable sources, this work offers the first comparative assessments of historic and projected population ionizing radiation doses in the U.S. from both the commercial nuclear electricity industry and several non-nuclear industries. In these assessments, it is shown that just a few non-nuclear industries have produced annual radiation doses to millions of Americans for decades that exceed what has been or likely ever will be produced by either the current or expanded use of commercial nuclear electricity. Such information may also be useful in setting acceptance criteria for beyond-design-basis events hypothesized to occur in the nuclear fuel cycle, as well as for public education. From these comparative assessments, it is concluded that current or expanded use of nuclear energy in the U.S. offers no significant threat of population doses from ionizing radiation that even approach the normal radiation doses historically experienced by the public resulting from many other industries.

Keywords: Ionizing radiation dose assessment; Population dose; Nuclear power industry; Radiation exposure; U.S. population exposures; Comparative radiation exposures

1. Introduction

The 21st century has arrived and brought with it a growing consensus that energy supply will be one of the larger challenges facing the U.S. and the world over the coming decades. The alternative to stimulate renewed commercial nuclear energy development is now being openly discussed in civil and dispassionate tones reminiscent of the 1960s. Such discussion is indeed timely, if not long overdue: extrapolating from predictions in Deutch et al. (2003), referred to hereafter as the MIT study, and U.S. Department of Energy (USDOE) (2006) for the next 25 years, it seems possible that U.S. electricity needs could double or triple over the next 50 years or so, and all current electricity production plants will have to be replaced during that same period.

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The current rejuvenation of public interest in commercial nuclear energy can only be sustained by using a different strategy from that of the 1960s, because two generations have a learned "fear of fission" based upon perceptions that nuclear energy is uniquely associated with ionizing radiation and that any amount of radiation is an undetectable cause of cancer. This fear has produced an imbedded damnation-of-radiation mentality within U.S. society, a phenomenon which has been reviewed in several studies, most recently in the MIT study and in National Academy of Sciences (NAS) (2006). The MIT study lists one of four unresolved problems limiting the renewed growth of commercial nuclear energy as its "perceived adverse safety, environmental, and health effects". Similar opinions from other highly respected and international institutions echo this concern, as shown in Allison (2006) from Oxford University. Whether discussions about nuclear energy relate to plant operational safety, or environmental effects, or militant acts of destructiveness (MADness) by terrorists, or nuclear spent fuel storage and transport, or ultimate nuclear waste disposal, the foundation of the fear is the exposure of people to radiation that might result.

Albert Einstein is reported to have defined insanity as doing the same thing over and over again, but expecting different results. If this fear of fission is not addressed early and often during the second coming of nuclear energy, the outcome may be much like that of the 1970s. The USDOE's Director of the Office of Civilian Radioactive Waste Management (OCRWM), Mr. Edward F. Sproat III, understands a different approach is required. In testimony before Congress (Sproat, 2006), he says that, as part of his four priorities, he intends "to put into place processes which maximize the ability of the public to understand the risks and mitigating safety factors" related to nuclear spent fuel transportation. Expanding upon this concept, the proper strategy for moderating the political outcomes of the fear of fission may be summarized as a simple axiom: when the public understands, the politics will work.

Perception of relative risk is a key determinant of radiation fear, and what the public has not previously been presented is a rational comparison of radiation doses from various industries. A unique first step, then, in addressing radiation fears might be the comparison of what is historically "normal" for public radiation dose from conventional industries with public radiation doses from the commercial nuclear fuel cycle. The MIT study has shown that education can change opinions and preferences of people with respect to the use of nuclear energy. This offers encouragement that a unique approach to public education about normal radiation doses from conventional industries – what people experience year to year, decade to decade throughout their lives – may diminish fears about far lower radiation doses from commercial nuclear energy.

This paper establishes a basis for, and a first attempt at, those comparisons, but nothing herein calls for, or endorses consideration of, a reduction in regulations or standards applied to the use of commercial nuclear energy. Adherence to current standards and regulations has made commercial nuclear generation a demonstrably safe technology, and this paper shows how little radiation dose to U.S. populations results from commercial nuclear generation when compared to doses from even a small subset of conventional, non-nuclear industries.

2. Materials and methods

2.1. Overview

More than a dozen industries expose their workers and the public to ionizing radiation levels greater than a background level, including the aviation, building design/construction, potable water supply, agriculture, construction materials, oil production, mining, and fossil fuel combustion industries, among others, as discussed in Pennington (2006). These industries do not use or produce man-made radionuclides, but typically reconfigure, redistribute or disperse Naturally Occurring Radioactive Material (NORM), composed primarily of potassium (^{40}K) and isotopes from the uranium, thorium, and actinide primordial series found within the makeup of the earth's crust, the leftover "nuclear waste" from the formation of the universe. U.S. Geological Survey (USGS) (1993) information shows the distribution of these primordial series radionuclides within the conterminous U.S., demonstrating their great variability in concentration. When human activities reconfigure, redistribute, or disperse NORM, the NORM is termed as Technologically Enhanced NORM (TENORM). Technologically Enhanced Natural Radiation (TENR) results from TENORM or from people being in closer or less-shielded proximity to natural radiation due to human actions. TENR is a byproduct of human activities that have occurred for decades, centuries, or eons and may be reduced by controlling such human activities.

NORM radionuclides are just as hazardous as man-made radionuclides, and we receive radiation from them continually, both internally and externally, throughout our lives. The relative risk from inhaling, ingesting, or being exposed externally to the radiation from man-made radionuclides like plutonium (^{239}Pu) and cesium (^{137}Cs) has been compared to that for NORM radionuclides in Pennington (2006) using cancer mortality risk coefficients from U.S. Environmental Protection Agency (USEPA) (1999). The comparison demonstrates that, on a per-unit-of-radioactivity basis, NORM is at least as hazardous as man-made radionuclides.

2.2. Ionizing radiation population exposure pathways

The non-nuclear industries of aviation, building design/construction, potable water supply, construction material, and agriculture have been selected for comparison herein with the commercial nuclear industry.

2.2.1. Commercial nuclear industry exposure pathways

The National Council of Radiation Protection and Measurements (NCRP) is a non-profit corporation, chartered by Congress in 1964 to collect, analyze, develop, and disseminate information and recommendations about radiation measurements, quantities, and units. In NCRP (1987a), the various stages of the nuclear fuel cycle are evaluated for their contribution to public radiation exposure in the U.S., based predominantly on data from the1980–1987 period. The discrete stages of the commercial nuclear fuel cycle include: uranium mining and milling of the extracted ore; ore conversion for enrichment in the fissionable uranium isotope ^{235}U and the enrichment process itself; fabrication of nuclear fuel for use in reactors; reactor operations; and the storage, transportation, and disposal of associated waste forms. Another area, which figures most prominently in the fear of fission, is the public radiation dose that could result from accidents or MADness events. While NCRP (1987a) does not explicitly address these exposure pathways, there are other sources for assessing such exposures.

2.2.2. Aviation industry exposure pathway

Flying at virtually any altitude causes a reduction in the natural shielding against galactic cosmic radiation provided by the gases and particulate matter in the atmosphere, meaning that there is more cosmic radiation available to interact with human bodies. As a result, people that fly in commercial, private, corporate, or military aircraft experience an increase in their exposure to ionizing radiation from outer space. Bailey (2000) reports the amount of cosmic radiation doubles with every 2000 m of increased altitude.

2.2.3. Building design/construction industry exposure pathways

The U.S. Census Bureau (USCB) (2005) shows the U.S. has almost 120 million housing units, and commercial and industrial buildings number in the many millions. The industry responsible for designing and building these structures for human occupancy is also responsible for the air quality within. Radon, or ^{222}Rn, and its four daughter products become "trapped" in buildings after entering occupied spaces, becoming major contributors to human ionizing radiation exposure. If the ambient or "background" levels of radon in outdoor air, about 0.015 Bq/L from NAS (1998a), were maintained in buildings, human exposure to this TENR would be radically reduced. Currently, however, indoor levels of radon can reach more than 50–100 times these outdoor levels, as shown by USEPA (1993b,c), NAS (1998a), and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2000a), significantly increasing the collective ionizing radiation dose of U.S. populations.

2.2.4. Potable water supply industry exposure pathway

Water systems and the supply of water to homes and businesses for drinking and cooking comprise the potable water supply industry. All potable water originates from terrestrial sources and many radionuclides may become dissolved or suspended in the water. As reported by NAS (1998b), when the water is delivered to homes or businesses and is consumed by occupants, the ingested radionuclides deliver ionizing radiation exposure to the person ingesting the water, thereby increasing TENR doses to U.S. populations.

2.2.5. Construction materials industry exposure pathways

The use of a variety of construction materials in structures, roads, or sidewalks, including stone, concrete, brick, tile, cinder block, or asphalt, can produce increased radiation exposure to people who live and work in those structures because of the increased NORM concentration in the material as the result of human activities. Indeed, such exposure pathways have been enhanced over the last decade through programs by the EPA and others to include Coal

Combustion Products (CCPs) in various construction materials (concrete, cinder blocks, brick, asphalt, etc.) as a method of recycling such waste products. USEPA (2005) summarizes these uses. CCP retains high levels of NORM from the coal, and the waste products increase the content of radioactivity in the medium used for their recycle.

Construction materials can also result in elevated TENR exposure to people who work in some relative proximity to shopping or business districts with an abundance of masonry buildings, paved streets, sidewalks, plazas, and parking lots. Such workers include police and fire fighting personnel, emergency response teams, construction workers, delivery people, sanitation workers, maintenance and service crews, parking facility staff, and street vendors.

2.2.6. Agriculture industry exposure pathways

Outdoor cultivation increases the ionizing radiation exposure of both farm workers and people that live close to farms. Soil contains an abundance of NORM. Left untended, soil is compacted by settling and moisture, and can be covered with dense natural foliage, providing shielding of the radiation emitted by the soil's NORM. Farming keeps large sections of acreage bare of cover for part of the year and encourages low density growth of limited vegetation for the other part. Clearing, plowing, tending, weeding, watering, and harvesting result in exposure to TENR: by removing the shielding of the natural foliage otherwise covering the fields; by loosening and aerating the soil, which reduces its self-shielding and increases the surface area of, and diffusion paths from, the soil for radon and thoron (^{220}Rn) radioactive gases; and by providing a large source of both radioactive wind-borne dust and radon and thoron gases. Storage, handling and application of fertilizers, which have even higher concentrations of some NORM radionuclides than soil, also contribute to TENR exposure. Finally, people associated with farming spend many hours in close proximity to these sources, increasing their exposure to both TENR and cosmic radiation. Therefore, farming causes elevated radiation doses to farm workers and people living in close proximity to farms.

2.3. Population exposures: nuclear and non-nuclear industries

In the following discussions, "background" radiation is an approximate expression of that unavoidable and irreducible exposure of people to natural sources and concentrations of ionizing-radiation-producing materials. In the U.S., the average annual Total Effective Dose Equivalent from natural sources of radiation is about 0.1 cSv/year, and is comprised approximately of 25% from terrestrial, 25% from cosmic, and about 50% from radon (^{222}Rn) sources. Sometimes, the term "background" radiation is used elsewhere to mean the "normal" exposure of the average U.S. citizen to all radiation sources, which is currently estimated to exceed 0.3 cSv/year, but background radiation, as used herein, is defined above. Additionally, the term "dose" is used herein to mean the Total Effective Dose Equivalent (TEDE), the sum of the effective dose equivalent (external exposure) and the 50-year committed effective dose equivalent (internal exposure). Population or collective dose is the sum of the TEDE for individuals in a specified population for a given period of time from a specified source of radiation and is termed the Collective Effective Dose Equivalent (CEDE).

2.3.1. Commercial nuclear fuel cycle population exposures

The commercial nuclear fuel cycle has existed in the U.S. for about 50 years. NCRP (1987a) provides an assessment by experts of population doses from the nuclear fuel cycle, based upon data taken from as early as 1980. The assessment shows population doses that would result from fuel cycle operations to support a commercial nuclear power plant producing a rated power of 1000 MWe, or about 3300 MW of reactor thermal power, delivering 80% of its design electrical output over a year. Table 1 summarizes the results presented in Section 15 of NCRP (1987a, Table 15.3). There are other similar assessments by experts of population dose resulting from commercial nuclear power, one of the more recent being UNSCEAR (2000b). However, UNSCEAR (2000b) provides a global assessment, while the NCRP (1987a) assessment focuses on U.S. populations. Additionally, the NCRP (1987a) assessment, when adjusted as shown in Table 1, results in higher, more conservative population doses than does UNSCEAR (2000b), by a factor of between two and four, depending on the approach used by UNSCEAR. Therefore, the more conservative assessment has been used herein.

The data which NCRP used for its assessment do not reflect many of the changes in standards, practices, and regulatory requirements over the last quarter century, and are estimated to be conservatively high, especially for the uranium mining and milling stages. Also, the NCRP assessment assumed a plant operating at an 80% capacity factor with

Table 1
NCRP assessment for annual Collective Effective Dose Equivalent (CEDE) to regional U.S. populations normalized to a 1000 MWe reactor at 80% and 90% capacity factors

Fuel cycle stage	Annual CEDE (person-cSv/year)
Uranium mining	94
Uranium ore milling	25
Uranium conversion	0.03
Uranium enrichment	0.01
Fuel fabrication	0.004
Reactor normal operation	4.8
Spent fuel and waste transportation	
Incident-free transportation	7.1
Transportation accidents	5.4
Low-level waste storage	No estimate available
Annual CEDE at 80% plant capacity factor	137
Annual CEDE at 90% plant capacity factor	154
Annual CEDE at 90% capacity factor with assumed population increase of 23% to 2006	190

regional populations at 1987 levels. Today's plants operate in the range of 90%, and, with a national population increase of some 23% from1987 to 2006, linear corrections for both factors have been included in Table 1, which overstate their impact. Further, while the NCRP assessment does not include population doses from low level waste storage and disposal or from dry spent fuel storage at reactors, which would be very small, it does include relatively high population doses for incident-free transportation and transportation accidents that simply have not occurred. Specifically, much less than 2 person-cSv of the transportation accident dose would more than cover low level waste and dry spent fuel storage population doses. The remainder of the transportation dose simply contributes to the conservatism of the assessment. Finally, the NCRP assessment does not include worker occupational doses, nor does it account for population doses from accidents during power plant operations or from spent fuel disposal in a repository. These will be addressed separately, below. In summary, the assessment in Table 1 is likely higher than actual results from the operation of the commercial nuclear fuel cycle over the last two decades. This is supported by the UNSCEAR (2000b) assessment. With doses already very low, however, improved accuracy becomes unnecessary for comparative assessment purposes.

Currently, there are 103 operating commercial nuclear generating plants in the U.S. Assuming that each is a 1000 MWe plant (the average is really about 980 MWe) and using the data from Table 1, the annual U.S. population collective dose from the commercial nuclear fuel cycle would be about 19,600 person-cSv. This does not include annual worker doses at U.S. nuclear plants, nor, for future considerations, does it consider potential population doses from a reactor accident or MADness event.

Operational worker doses at commercial nuclear generating plants are tracked and reported on a regular basis by the U.S. Nuclear Regulatory Commission (USNRC). For calendar year 2004, about 150,000 monitored nuclear workers at commercial nuclear generating plants received about 10,400 person-cSv of collective dose, as reported in USNRC (2004a). Adding this to the estimate in Table 1, the annual collective dose would be less than 30,000 person-cSv for 2004. Annual doses in this range have occurred for the last decade or so, based upon about the same number of power plants in operation.

Using the data sources previously cited, and adding reasonable estimates for the early years of nuclear fuel cycle operations, a bounding value for the public and worker collective dose over the last 50 years from the commercial nuclear fuel cycle would amount to population doses from Table 1 sources of about 200,000 person-cSv from 1956 through 1989 (including the Three Mile Island event), population doses from Table 1 sources of about 300,000 person-cSv from 1990 through 2006, worker doses of 120,000 person-cSv from 1956 through 1972, and worker doses of 960,000 person-cSv from 1973 through 2006. This amounts to something less than 1,600,000 person-cSv over the last 50 years from the commercial nuclear fuel cycle for a national population average that would exceed 200 million people. With the estimates in Table 1 previously cited, the true collective dose is likely much lower, but for comparative assessment purposes, this bounding estimate offers sufficient accuracy for an historical perspective on the radiological impact of commercial nuclear generation.

However, a prospective view over the next 50 years of nuclear electricity generation is also desirable, especially if a tripling of nuclear electricity generation occurs, as the MIT study suggests is necessary. One can perform a similar assessment to that for the historical review to determine what population exposures might occur. For the future, however, accidents and MADness events at commercial nuclear generating plants could result in population doses that might be higher than historic values. The only accident at U.S. commercial nuclear generating plants over the last 50 years that has produced even a modest population dose was the accident at the Three Mile Island (TMI) Unit 2 plant in 1979, which USNRC (2004b) reports as a severe core meltdown that resulted in a collective dose of about 2000 person-cSv for a population of about 2 million people. These data, along with other smaller releases from U.S. commercial reactors over the last 50 years not resulting from a core damage scenario, can be used as a sample for hypothesis testing to project the bounding values of population doses that might be expected from a future accident at a Western-style reactor. However, such an approach yields a fairly low collective dose, which may not be sufficiently conservative and does not take into account some consideration of accident frequency.

A more conservative approach for assessing a bounding estimate for collective doses from a commercial nuclear generating plant resulting from an accident or MADness event would be to use expert assessments of accident frequencies and extrapolate U.S. population doses from those in the Former Soviet Union (FSU) resulting from the Chernobyl Unit 4 event in the Ukraine in 1986. The Chernobyl event was a core ejection and "burn-up" accident as a result of a steam explosion from a rapid power excursion that provided a significant radioactive material dispersal plume due to the explosion and to the thermal conditions from the burn-up. Further, the plant was without even a rudimentary containment structure around the reactor. Table 2 shows the 50-year collective dose to the people of the FSU resulting from the Chernobyl accident is something less than 10.7 million person-cSv, as conservatively calculated by UNSCEAR (2000c). These population doses were greatly exacerbated by the type of reactor, the rapid release of radioactivity from the accident as the result of no containment system, the need for emergency responders to deal with highly radioactive reactor core material ejected by the accident, the proximity of the population around Chernobyl, and the continued consumption of local foodstuffs, post-accident, from the Chernobyl region.

Western-style reactors have inherently safer core designs, along with containment structures to mitigate radionuclide release in the event of accidents and more backup and safety systems than existed at Chernobyl. The TMI accident demonstrated the effectiveness of containment structures by limiting radionuclide releases to the environment from a severe meltdown. Differences in the containment and safety systems, as well as the timing of releases (especially the cesium and thyroid-seeking iodine isotopes), the type of release (thermal plume from a burn-up versus a meltdown), the proximity of the local population, and the consumption of local foodstuffs likely make the Chernobyl population doses well beyond anything credible for an accident at a Western reactor. However, one can use these FSU population doses, together with current assessments of experts about Western reactor safety, to reasonably estimate the upper bounds of population doses due to future accidents and MADness events at U.S. reactors for the next 50 years or so.

The MIT study provides expert analysis about reactor core damage frequencies during operations over the next 50 years. Such analysis says that, for no enhancement of reactor safety technology and a more than tripling of commercial nuclear power plants, four core damage events would be anticipated globally in the next 50 years for up to 1000 GWe

Table 2
Collective Effective Dose Equivalent (CEDE) to the inhabitants of contaminated areas in the Russian Federation, Belarus, and the Ukraine resulting from the Chernobyl accident

Type of exposure	CEDE (person-cSv)
External	4.03 million
Internal	2.04 million
Thyroid (short term)	4.6 million
CEDE	10.67 million
Average annual CEDE for 50-year lifetime for 5.2 million people in the FSU	0.041

Note: UNSCEAR (2000c) has provided collective dose estimates based upon calculations. Paragraph 171 of UNSCEAR (2000c) reports external doses were calculated based upon average cesium deposition densities to estimate annual collective doses. Using computational models rather than actual measured dose rates, potential shielding, and exposure periods tends to overestimate doses, typically in the range of 20–60%. Paragraph 172 states internal doses were calculated based upon average cesium deposition densities. However, paragraphs 158 and 159 point out that whole-body counting was also used in some measurements and, on average, showed that calculated internal doses could be high by a factor of 3 or more. Therefore, it is likely the doses reported in this table are higher than actual doses by some significant percentage.

(GWe, a term for 1000 MWe) of global nuclear electricity generation. The MIT study reports advanced reactor designs projected for use in the U.S. over the next 50 years exhibit roughly a 10-fold decrease in the likelihood of a serious reactor accident, but for bounding assessment purposes, that improvement is not considered herein. Further, the MIT study's conclusions on global use of nuclear power would say that about 30% of those core damage events would occur in the U.S. and that about 10% of such events would result in a containment system failure. Failure of the containment system does not imply a full dispersion to the environment of the total radionuclides released from the reactor core; it just means that a greater release might occur than if the containment did not fail. But for purposes of simplification, it is assumed that containment failure results in the same population doses as Chernobyl, in proportion to, or weighted by, the probability of the containment failure, in order to establish an expected value. To assure that MADness events are fully considered in estimating an upper bound of population dose, it is assumed that all four global core damage events in the next 50 years projected by the MIT experts will occur only at U.S. reactors. This would mean that, over the next 50 years, four such accidents would result in something less than 1.1 million person-cSv each for a 50-year total from four such events of less than 4.4 million person-cSv of population dose in the U.S.

As another consideration, dry spent fuel storage at reactors and transport of spent fuel to a repository in cask systems should also be considered for their potential of accident and MADness event releases to the public in more detail than the NCRP analysis from Table 1. A recent study, NAS (2006), shows that the largest releases from accidents would result in about 10,000 person-cSv, based upon a very conservative calculation. The work on which the NAS report is based, USDOE (2002), also shows a terrorist event might result in 17,000 person-cSv for a rail-size spent fuel transport cask. Though no such accidents or MADness events have ever occurred, it is conservatively assumed that one such event with population doses of 20,000 person-cSv would occur every 5 years for the next 50 years to account for spent fuel transport and storage accidents, as well as MADness events, that might arise from a much larger commitment to commercial nuclear electricity. This would result in a total additional population dose of 200,000 person-cSv.

Finally, the spent fuel and nuclear waste repository at Yucca Mountain, Nevada, are scheduled to begin operation in the next 10–15 years. The repository will require about 5 years for construction, followed by about 50 years to complete loading to its current design capacity. USDOE (2002), Section 4, provides detailed analysis of both worker and public population doses that result from these phases of repository operation. If it is assumed that the repository is licensed by the NRC very quickly and can begin construction in 2011, then, after construction, there would be 42 years of repository loading operations in the next 50 years. Based upon the USDOE (2002) analyses, the first 5 years for construction would result in much less than 1000 person-cSv to both workers and the surrounding population within 50 miles of the repository (some 76,000 people). Of interest is that none of that exposure would come from nuclear waste, but from the increase in natural radon released to the atmosphere during the subsurface construction of the repository. While this is not a population dose that results from nuclear waste, it is included in the USDOE analysis for conservatism.

During the succeeding 42 years of repository loading operations, the dose to the surrounding population would be less than 1000 person-cSv, greater than 99.9% of which would be from increases in natural radon emitted by the repository. Doses to workers would be less than 10,000 person-cSv over that period, some of which would also result from natural radon and some of which would result from the military nuclear waste also buried there, which does not result from the generation of commercial nuclear electricity. Even if several radiological accidents were to occur at the repository, worker doses would increase by less than 10% over that 42 years and surrounding population doses by about 5%. Therefore, over the next 50 years, the nuclear waste at the Yucca Mountain repository will contribute much less than 13,000 person-cSv to the total population dose resulting from the commercial nuclear fuel cycle.

With these conservative assumptions, bounding U.S. population doses over the next 50 years from accidents, MADness events, and the operation of the Yucca Mountain repository would be something less than 4.6 million person-cSv.

The bounding estimate for the collective dose resulting from the commercial nuclear fuel cycle over the next 50 years may be completed by using the MIT projections to arrive at an average installed nuclear capacity over the next 50 years of 200 GWe, applying the population doses calculated using NCRP's analysis from Table 1 to arrive at 38,000 person-cSv/year, adding in worker doses consistent with today's levels at 22,000 person-cSv/year, and, finally, including population doses from potential accidents and MADness events, as well as from the Yucca Mountain repository. The bounding estimate would be comprised of less than 3 million person-cSv from the commercial nuclear fuel cycle population and worker exposures, and less than 4.6 million person-cSv from commercial nuclear accidents, MADness events, and the operation of the Yucca Mountain repository. This amounts to less than 7.6 million person-cSv to supply a sizable fraction of the U.S. electricity needs over the next 50 years.

2.3.2. Non-nuclear industries

A number of publications over the years have cited various elements of conventional industry radiation exposure of the public [see, for example, NCRP (1987b)]. Recently, the results of an assessment of the annual U.S. population doses exceeding background levels for the aviation, building design/construction, potable water supply, and agriculture industries were presented in Pennington (2006). That assessment used models and methods from similar studies and incorporated input data from reliable published sources. Further, the methods and input data used were focused on providing assessments that likely understate population doses, contrary to the approach taken by safety analysis methods, which tend to emphasize bounding calculations. The following summarizes the results reported for each of these four industries.

2.3.2.1. Aviation industry. An air travel model was set up that included the population exposed, the average time involved with ascent and descent, the average time at cruise altitude, and the measured average dose rates from Lindborg et al. (2004) during ascent/descent and at the average cruise altitude to determine the population exposure. The modeling is applied solely to commercial airline travel for the U.S. and understates the total U.S. population exposure to cosmic radiation from flying because it ignores military flight crews and passengers, corporate flight crews and passengers, the more than 3 million passengers that fly annually on chartered aircraft, and the more than 550,000 non-commercial pilots that make up the general aviation community in the U.S. Currently, for commercial airline travel only, annual public and flight crew doses above background are greater than 0.46 million person-cSv. For the last 45 years, U.S. agencies have recorded and published annual passenger commercial air travel data, and using this data, it is estimated that commercial air travel has resulted in a collective dose above background over that period of more than 12 million person-cSv.

2.3.2.2. Building design/construction industry. NAS (1998a) reports on the indoor exposure of the U.S. population to radon (^{222}Rn) in residences, relying for much of its data on Marcinowski et al. (1994). UNSCEAR (2000a) and the USEPA also present dose assessment methodologies for indoor TENR exposures from radon, as well as radon concentration data (see USEPA (1993b,c), for example). Data collected from these sources show the highly lognormal distribution of radon concentrations in houses. Several models using this data were developed to assess realistic total committed doses from radon. As reported, the calculated annual collective radon dose above background to U.S. populations resulting from the building design/construction industry for the current population size is in the range of 15 million person-cSv. Over the last 50 years, adjusting for population size, the building design/construction industry has produced a collective dose above background of at least 430 million person-cSv.

2.3.2.3. Potable water supply industry. Radon and radium (^{226}Ra) are major contributors to ingestion exposure of U.S. populations, and NAS (1998b) reports on the studies of such exposures. Modeling was developed using NAS data for radon distribution in potable water to calculate annual U.S. ingestion doses to ^{222}Rn and also to ^{226}Ra (as a surrogate for all other NORM radionuclides) in much the same fashion as radon doses from inhalation in residences was performed. Current annual population doses above background in the U.S. exceed 1.5 million person-cSv, and over the last 50 years, the potable water supply industry has produced more than 38 million person-cSv of U.S. population collective dose above background.

2.3.2.4. Agriculture industry. A model set was developed for farm workers and for the Critical Population Group (CPG) that lives within 200 m of a farm, based on similar models that the USEPA assembled for performing preliminary risk assessments of diffuse NORM wastes in USEPA (1993a). The model set evaluates annual collective doses resulting from farming in each state and totals U.S. population doses over evaluated exposure pathways to arrive at the national collective dose. To assure likely understatement of population doses resulting from farming, only direct gamma dose, outdoor fugitive dust inhalation dose (ignoring all ^{40}K in soil and fertilizer), and outdoor radon/thoron (^{220}Rn) gas inhalation dose were evaluated. All indoor inhalation and ingestion doses generated by farming were also ignored. Based on these assessments, the current annual collective dose above background to both farm workers and

Table 3
Annual Collective Effective Dose Equivalent (CEDE) to U.S. populations above background resulting from four non-nuclear industries

Industry	Total exposed population (people)	Total exposed population annual CEDE (person-cSv)	More highly exposed population (people)	More highly exposed population annual CEDE (person-cSv)	Most highly exposed population (people)	Most highly exposed population annual CEDE (person-cSv)
1. Aviation						
General public	31 million	4.3×10^5	20 million	3.5×10^5	310,000	1.4×10^4
Workers	176,000	2.9×10^4	157,000	1.8×10^4	19,000	1.1×10^4
2. Building design, construction						
General public	142 million	14.9×10^6	3.2 million	3.4×10^6	1.4 million	1.8×10^6
3. Potable water supply						
General public	266 million	1.5×10^6	38.4 million	1.1×10^6	1.5 million	1.5×10^5
4. Agriculture						
General public	19.6 million	1.1×10^6	12.6 million	8.7×10^5	2.2 million	2.0×10^5
Workers	2.5 million	1.9×10^5	1.7 million	1.4×10^5	220,000	3.2×10^4

the CPG is greater than 1.3 million person-cSv, and the total collective dose above background over the last 50 years exceeds 52 million person-cSv.

Table 3 summarizes annual U.S. population doses for each of these four industries, while also presenting data on sub-populations that receive higher doses because of the lognormal nature of dose distributions.

2.3.2.5. Construction materials industry. Construction materials include masonry, concrete, brick, tile, and asphalt for use in houses, buildings, roads, sidewalks, malls, plazas, parking garages, and the like in both residential and commercial settings, and they are a source of population exposure to ionizing radiation on which NCRP (1987b) and others have reported. Countries in the European Union (EU) have developed and published assessment models for determining exposures as part of their plans to limit such population doses. Using models from Finland reported in Markkanen (1995) and from NCRP (1987b), and typical source terms for building materials from European Commission (1999), combined with U.S. Department of Labor (USDL) Bureau of Labor Statistics data from USDL (2006), assessments of the doses above background to occupants of structures constructed with high NORM contents, workers external to such buildings in metropolitan areas, and public visitors to these areas have been made.

For doses to occupants of residences, schools, and work places constructed of masonry or concrete materials having NORM content, NCRP (1987b) developed an assessment model that has been used herein, but with updated source terms from European Commission (1999). Additionally, dose assessment models from Markkanen (1995) have been used to calculate dose rates external to large structures having construction materials with NORM content. Further, assuming a limited set of metropolitan areas in the U.S. (only those with 100,000 jobs or greater), and using subsets of USDL (2006) data for various labor categories that work external to such structures in the selected metropolitan areas, annual doses above background to these labor groups can be calculated. Finally, annual doses above background to infrequent visitors to such areas for shopping, dining, or limited business purposes can be similarly calculated. Table 4 provides the population sizes and annual doses for this assessment of the U.S. construction materials industry.

3. Results

Table 5 provides a summary of the annual population doses of the five non-nuclear industries in relation to the current population doses from the commercial nuclear industry. It also provides the projected population doses over the next 50 years, assuming in all cases that the U.S. population size remains constant. In order to assure that the assessment of the population doses from the five non-nuclear industries tends towards underestimate, it is assumed that their annual population doses remain at current levels over the next 50 years and do not increase with growth and expansion of the industries. For additional conservatism, the population dose from the commercial nuclear industry is projected to increase sharply due to both extraordinary growth in nuclear generated electricity and the assumption of multiple,

Table 4
Annual Collective Effective Dose Equivalent (CEDE) to U.S. populations above background resulting from the construction materials industry

Population groups	Effective population (people)	Annual CEDE (person-cSv)
1. Metropolitan area (>100,000 jobs)		
External labor categories		
Personal service	280,000	7800
Transport, moving	3,100,000	87,000
Equipment installation and maintenance	60,000	1700
Cleaning and maintenance	2,100,000	59,000
Police and security	1,500,000	42,000
Sales	10,000	300
Construction and repair	2,200,000	61,000
2. Metropolitan area (>100,000 jobs)		
Other groups		
Other workers	50,000,000	186,000
Visitors, shoppers	150,000,000	279,000
3. Building occupants	153,000,000	1,300,000
Total population dose		>2,000,000

Note: All calculated values are based upon average NORM content, average work periods, shielding from radiation while outside, and average stand-off distances from external walls of 10 m. Because the distribution of NORM content in U.S. construction materials has not been reported, the effect of the lognormal distribution of such materials is not presently quantifiable. However, high exposure populations from lognormal distributions typically constitute about 1–5% of the total population. Using a percentage of 2.5 of the External Labor Categories in group 1 above, together with the maximum NORM concentrations in construction materials from European Commission (1999), a population of about 230,000 workers would receive a collective annual dose of about 68,000 person-cSv above background, for an average annual TEDE of about 0.3 cSv.

but highly improbable, accidents that produce Chernobyl-like population doses based on an expected value for containment failure.

Another assessment examines comparatively what might be termed the Elevated Dose Effective Population (EDEP), comprised of groups receiving peak annual exposures from non-nuclear industries relative to background levels. From Tables 3 and 4, the EDEP for these industries could be selected as the 3.4 million people that receive annually some 3.5 million person-cSv above background. There are smaller population subsets with groups of 350,000 or so people that receive more than 0.7 million person-cSv annually. Such numbers may be compared to the doses for the commercial nuclear industry worker population subset, where 150,000 monitored workers receive about 0.01 million person-cSv annually. With less than half the total of monitored nuclear workers receiving almost all the exposure, the total EDEP dose for nuclear workers is still more than 300 times lower than the EDEP dose for the non-nuclear industries.

The direct comparison of these results to the Chernobyl population doses is also of interest. UNSCEAR (2000c) shows that the highest annual collective dose from Chernobyl occurred in the first year. The exposed population of

Table 5
Comparative Collective Effective Dose Equivalent (CEDE) to U.S. populations above background from five non-nuclear industries and from the commercial nuclear industry

Industry	Current annual CEDE (person-cSv)	Estimated previous 50-year CEDE (person-cSv)	Projected 50-year CEDE (person-cSv)
Aviation	>0.46 million	>12 million	>23 million
Building design/construction	>14.9 million	>430 million	>745 million
Potable water supply	>1.5 million	>38 million	>75 million
Agriculture	>1.3 million	>52 million	>65 million
Construction materials	>2 million	>78 million	>100 million
Total for five non-nuclear industries	>20 million	>610 million	>1 billion
Commercial nuclear industry	<0.03 million	<1.6 million	Without accidents, <3.0 million With accidents, <7.6 million

Table 6
Elevated Dose Effective Populations (EDEPs): comparative Collective Effective Dose Equivalent (CEDE) and average annual Total Effective Dose Equivalent (TEDE) for selected industries and events

Industry/event	EDEP (people)	Annual or lifetime CEDE (person-cSv)	Average annual TEDE (cSv)
Aviation	19,000	1.1×10^4/year	0.6
Building design/construction	3.2 million	3.4×10^6/year	1.1
Construction materials	230,000	6.8×10^4/year	0.3
Totals	3.4 million	3.5×10^6/year	>1.0
Commercial nuclear workers	70,000	1.04×10^4/year	0.15
Chernobyl FSU population			
First year	5.2 million	$<5.0 \times 10^6$	<1.0
Lifetime	5.2 million	10.67×10^6	0.04

5.2 million people in the FSU received less than 5 million person-cSv. The EDEP from the non-nuclear industries receives higher annual doses every year than the exposed FSU population received from Chernobyl during the highest dose year only. Table 6 summarizes this information.

4. Discussion

The preceding results seem adequately supportive of their proposed purpose from the introduction herein and are consistent with results from discrete investigations of smaller industry and population segments by others, as reviewed by Pennington (2006). Several additional issues associated with these results suggest further discussion because they are material to the consideration of the conclusions that follow. These are highlighted below.

- Much of the supporting information for these assessments has been understood for decades by those that advocate for, those that regulate, and those that oppose the use of nuclear energy. Yet, there has been little public health outcry about the lognormally distributed population doses from non-nuclear industries that exceed the worst of all commercial nuclear plant operations or accidents annually. Additionally, there seems to be a sense within government agencies and departments that their representatives are somehow obligated to extend a "professional courtesy" towards non-nuclear industries by not disclosing or discussing the population exposures to ionizing radiation that such industries cause annually. This may be one of the reasons why the public is ill-informed.
- The assessments herein have been intentionally based upon calculations that tend to overstate population doses from the commercial nuclear industry and understate doses from non-nuclear industries. Even so, it is recognized that differences in assessment methods and assumptions could result in projected outcomes that vary by some meaningful percentage. Even for very large percentage variations, however, the non-nuclear industries' normal population doses would still substantially exceed those that might result from the commercial nuclear industry.
- There may be a misperception that population doses from commercial nuclear energy are predominantly acute (short term) rather than chronic (long term), which, for some, might tend to increase the importance of nuclear versus non-nuclear industry population exposures. Population and operator doses from commercial nuclear industry normal operations are highly chronic, as demonstrated by the record. For reactor accidents, with the exception of iodine and first responder doses (all of which are minimized with a reactor that has a containment system), UNSCEAR (2000c) shows that population doses from commercial nuclear accidents will be chronic by a very large percentage, like doses from non-nuclear industries. Therefore, population doses from the commercial nuclear energy industry are chronic in very similar ways to those from non-nuclear industries.
- The comparative effects of population doses resulting from the commercial nuclear industry and from non-nuclear industries depend, in some measure, on the application of the Linear No-Threshold (LNT) hypothesis to ionizing radiation exposures. Since the LNT hypothesis is currently the foundation of ionizing radiation standards and impact assessment, the use of Collective Effective Dose Equivalent is a reasonable basis for comparative assessments among industries, especially considering that cancer mortality/morbidity risk coefficients for particular nuclides can present another increment of significant uncertainty.

- Of the six industries assessed herein, the two most modern industries (aviation and commercial nuclear energy) have, by far, the lowest impact on U.S. population ionizing radiation exposures. The other four industries have had consistently high participation in U.S. population exposure to ionizing radiation for decades or centuries. Perhaps this offers insight as to why those that fear nuclear energy have not sought to limit actual doses resulting from other industries.
- The usefulness of the assessment presented herein is its value in educating the public and political representatives on the comparative safety of commercial nuclear energy. Opinions about that value will vary. One indicator of the value, however, might be to imagine the political response if the population doses from the commercial nuclear industry and those from non-nuclear industries shown herein were reversed.
- How to evaluate, regulate, or set acceptance criteria/standards for nuclear system responses to terrorist and other beyond-design-basis events is one of the latest areas of perplexing investigation by nuclear regulatory bodies. Lognormally distributed non-nuclear industry annual collective doses make an ideal comparative measure for use as an acceptance criterion for the possible outcomes of beyond-design-basis accident assessments or MADness events involving the nuclear fuel cycle. Similarly, use of these comparisons would be most helpful for public understanding of the risk from such things as "dirty bombs" and other afflictions of the terrorist age.

5. Conclusions

1. Currently, the five non-nuclear industries assessed herein each produce substantially higher annual population doses from ionizing radiation than does the commercial nuclear industry. Each also produced more population dose over the last 50 years than the commercial nuclear industry, and each will likely produce substantially more population dose over the next 50 years, even if there is a pronounced expansion of commercial nuclear energy accompanied by highly unlikely scenarios of commercial nuclear accidents and MADness events.
2. These five non-nuclear industries together currently produce more than 650 times more annual population dose above background than the complete commercial nuclear industry fuel cycle. Over the past 50 years, these five industries have produced more than 350 times more population dose above background to U.S. populations than the commercial nuclear industry.
3. Over the next 50 years, even if significant but highly unlikely commercial nuclear accidents or MADness events occur, these five non-nuclear industries will still expose U.S. populations to more than two orders of magnitude more ionizing radiation dose above background than will result from the commercial nuclear industry.
4. If all of the four potential commercial nuclear accidents assumed herein to occur within the U.S. over the next 50 years resulted in population doses equivalent to those determined to have occurred in UNSCEAR (2000c) for the Chernobyl accident, each of the non-nuclear industries assessed herein, with the exception of the aviation industry, would still produce a 50-year population collective dose greater than that of the entire commercial nuclear industry.
5. Certain subsets of U.S. populations currently exposed to lognormal distributions of ionizing radiation from non-nuclear industries receive annual collective doses that are very high, even in comparison to the worst-year doses of the population in the vicinity of the Chernobyl accident. Simply stated, more than 1% of the total U.S. population receives CEDE exposures every year from non-nuclear industries that exceed average worst-year population doses from a significant reactor accident, and this has occurred for decades, if not centuries.
6. These assessments show that current or expanded use of commercial nuclear energy in the U.S. offers no significant threat of population doses from ionizing radiation that even approach the normal population ionizing radiation doses caused by other industries.

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